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Evolution of microstructure and texture during recovery and recrystallization in heavily rolled aluminum

O V Mishin[1], A Godfrey[2], T Yu[1], N Hansen[1] and D Juul Jensen[1]

[1] Danish-Chinese Center for Nanometals, Section for Materials Science and Advanced Characterization, Department of Wind Energy, Technical University of Denmark, Risø Campus, 4000 Roskilde, Denmark

[2] Key Laboratory of Advanced Materials (MOE), School of Materials Science and Engineering, Tsinghua University, Beijing 100084, China

E-mail: olmi@dtu.dk

Abstract. The annealing behavior of nanostructured aluminum AA1050 prepared by cold rolling to an ultrahigh strain (ε_{vM} = 6.4) has been investigated using both transmission electron microscopy and electron backscatter diffraction techniques, paying particular attention to changes in microstructure and texture during recovery and their influence on subsequent recrystallization. It is found that coarsening of lamellar structures during recovery can occur via triple junction motion, and that this process can modify the proportion of different boundary types and texture components compared to those in the cold rolled material. Additionally, the heavily deformed material is characterized by different textures and different spatial arrangements of rolling texture components in the center and subsurface. It is found that changes in the misorientation distribution and texture during coarsening are greatly affected by the initial spatial distribution of crystallographic orientations. In particular, the reduction in the fraction of high angle boundaries observed during recovery is much more pronounced in the subsurface layers than in the center layer. The initial through-thickness heterogeneity is thus greatly enhanced during recovery, which leads to significant differences in recrystallized microstructure and texture in the different layers.

1. Introduction

Materials deformed to high strains are characterized by very small boundary spacings and typically contain large fractions of high angle boundaries (HABs), which can result in a modified annealing behavior compared to materials deformed to low strains. For example, it has been recently reported that coarsening of deformation structures in heavily rolled aluminum may occur via triple junction (TJ) motion [1,2]. Depending on the spatial distribution of different texture components, such coarsening can lead to very different recovered microstructures in which subsequent recrystallization takes place [3]. This has been demonstrated in our previous electron backscatter diffraction (EBSD) study of an AA1050 sample cold rolled to a von Mises strain of 6.4, which had different proportions and different spatial distributions of rolling texture components in the center and subsurface layers [3]. In the present work, we complement the EBSD data with new transmission electron microscopy (TEM) observations of TJ motion, and discuss the evolution of texture and microstructural parameters during recovery and recrystallization in heavily rolled aluminum.

2. Experimental

A plate of aluminum AA1050 was cold rolled by multiple passes from 10 cm to ~0.4 mm. Cold rolling was conducted with lubrication, unidirectionally by alternating the top and bottom sides between passes, and applying predominantly intermediate draughts [4]. The cold-rolled material was then annealed in air at 300 °C for different periods of time. The microstructure and texture were characterized in the section containing the rolling direction (RD) and the normal direction (ND). For the deformed and recovered samples, EBSD maps were obtained in the center and at 30–130 μm from the surface. For texture analysis of all samples and for microstructural analysis of partially and fully recrystallized samples, the entire sample thickness was covered by EBSD. Each through-thickness data set was divided into three subsets of equal size to obtain information separately for the center and subsurface layers. The data from the two opposite subsurface layers were combined for determining boundary spacings, proportions of different boundary types and fractions of different texture components. In addition, thin foils were investigated in a JEM 2100 transmission electron microscope equipped with a double-tilt heating holder. The foils were heated to 270 °C within ~4 min, and then to 300 °C over a period of 2 minutes. TEM images were taken both in the cold-rolled condition and during in-situ annealing using a TVIPS FastScan camera.

3. Results and Discussion

Lamellar structures combined with microshear bands are seen in the heavily rolled microstructure (see Fig. 1). The EBSD data indicate that the dominant texture in the center is the S {123}⟨634⟩ component, whereas the texture in the subsurface layers is dominated by one of the symmetric variants of a component near the ideal Cu {112}⟨111⟩ orientation [3]. These dominant components compose broad texture bands subdivided both by HABs (between symmetric variants of one texture component) and by LABs. The broad bands are interspersed with narrower bands representing weaker components of the rolling texture, of which the Brass (Bs) {110}⟨112⟩ component was the weakest (Fig. 1). Interestingly, despite the significant differences in the spatial distribution of the rolling texture components, the average boundary spacing along the ND and the fraction of HABs are very similar in the different layers, being ~0.2 μm and 54–56%, respectively.

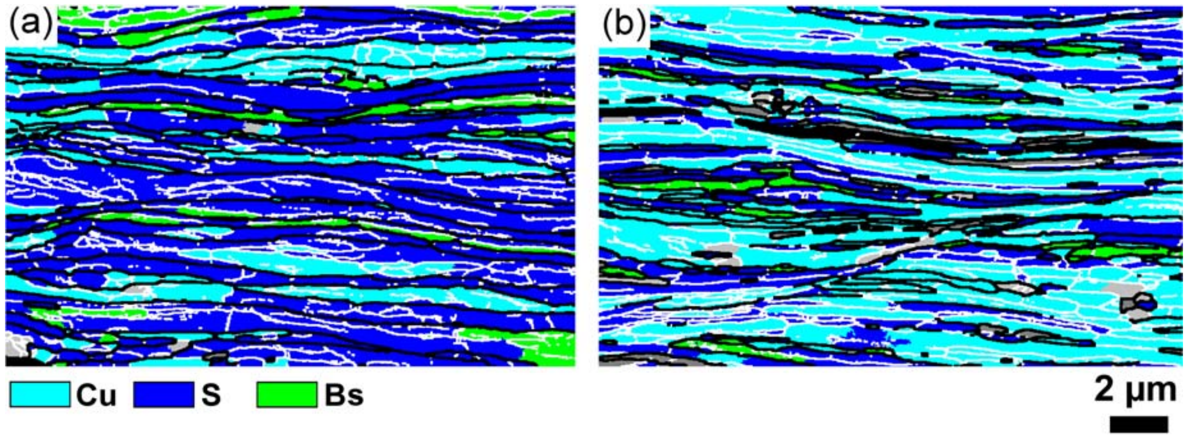

Figure 1. EBSD maps showing deformation structures in the center (a) and the subsurface (b) of the cold-rolled sample. LABs (θ =1.5–15°) and HABs (θ >15°) are shown by white lines and black lines, respectively. The RD is parallel to the scale bar. Reprinted from [3] with permission from Elsevier.

Upon annealing the microstructure coarsens during recovery, followed by pronounced discontinuous recrystallization after ~10 minutes at 300 °C. The coarsening occurs without significant changes in the lamellar morphology and is accompanied by reductions in the HAB fraction to ~40% in the center and 20% in the subsurface. The reduction in the fraction of HABs observed during coarsening in this work is consistent with several previous observations in heavily deformed and annealed materials [5–8].

In our previous publication [3], based both on EBSD maps collected after short-time annealing at 300 °C and on TEM findings in samples annealed at lower temperatures [1,2], the coarsening of the lamellar structures was attributed to TJ motion. In the present work, we reinforce this conclusion by direct TEM observations of TJ motion at temperatures approaching 300 °C. Although structural coarsening takes place already during the heating-up to 270 °C, significant changes continue to occur as the temperature approaches 300 °C. Figure 2 shows a sequence of TEM images taken during in-situ heating as the temperature reached ~290 °C. Initially the TJ marked by an arrow in Fig. 2a was pinned by an interconnecting boundary in a neighboring lamella on the left side (this interconnecting boundary is shown as a dashed line near the TJ marked in Fig. 2e). Within 0.37 s the TJ moved rapidly over a distance of ~2 μm (Fig. 2b), then slowed down as it migrated past two more interconnecting boundaries on the left side (Fig. 2c), after which the TJ moved rapidly again (Fig. 2d and Fig. 2f). The migration of this TJ therefore increased the boundary spacing in the inspected region (cf. Fig. 2e and Fig. 2f), while preserving the lamellar morphology.

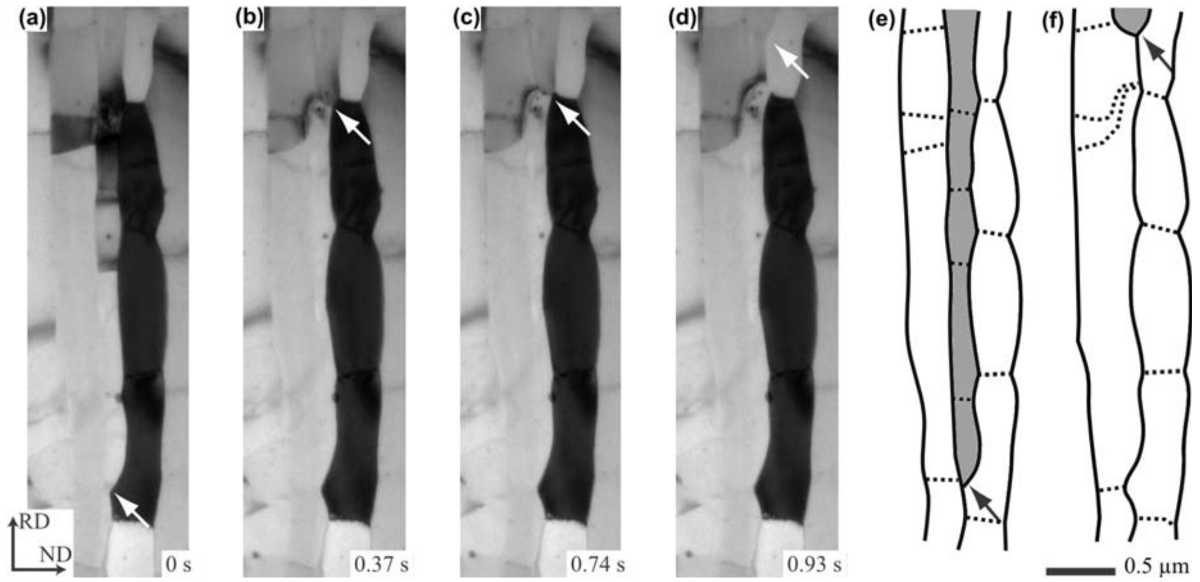

Figure 2. TJ motion observed in a TEM foil (center layer) at ~290 °C: (a-d) TEM images obtained after different periods of time (0 to 0.93 s), where a rapidly migrating TJ is marked by an arrow. The changes before and after the TJ motion are shown schematically in (e,f). Solid and dashed lines in (e,f) indicate lamellar and interconnecting boundaries, respectively.

Most subgrains and narrow lamellae of non-dominant texture components are located between coarser lamellae of the dominant texture components, and as such are typically surrounded by HABs. Therefore, their shrinkage by TJ motion leads to a reduction in the HAB fraction as newly formed boundaries between the broad lamellae of similar orientations are LABs (Fig. 3).

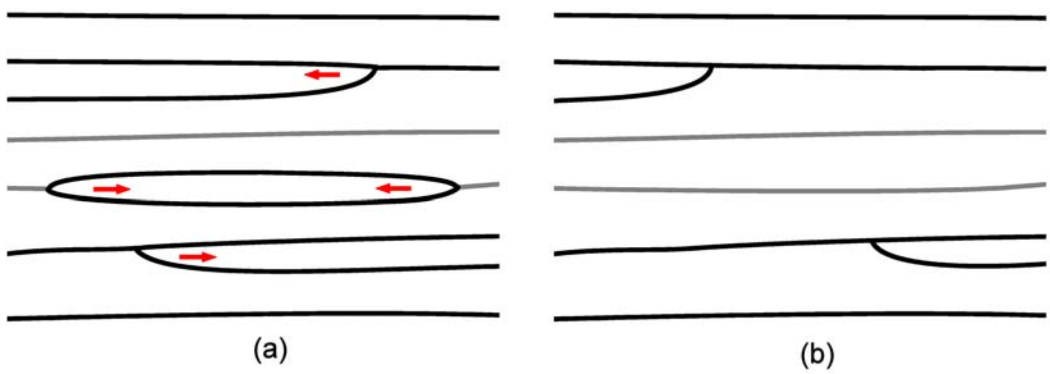

Figure 3. Schematic showing coarsening via lateral motion TJs in a deformed lamellar microstructure: (a) initial microstructure; (b) microstructure after TJ motion. Black and gray lines indicate HABs and LABs, respectively. Reprinted from [3] with permission from Elsevier.

Since in each subsurface layer there is only one dominant orientation variant, the reduction in the fraction of HABs in these layers is much more pronounced than in the center, where the dominant S component is represented by four symmetric variants [3]. Consequently, by the time pronounced recrystallization starts, the center still contains a high frequency of mobile HABs, whereas there are very few such boundaries left in the subsurface (see Fig. 2b). These differences in the frequency of mobile boundaries result in a very large difference in the frequency of recrystallization nuclei and in the recrystallization kinetics in the different layers. Accordingly, in the center layer, recrystallization was found to take place initially more rapidly and with a higher nucleation density, thus resulting in a smaller final grain size (13 μm) compared to that in the subsurface layers (~30 μm). In each layer, the nuclei were observed to form within lamellar structures and near coarse particles. The former ones typically had orientations of the rolling texture components, whereas nuclei near coarse particles had orientations of the rolling texture, or of the P {011}⟨566⟩, $\mathrm{Cube_{ND}}$ {001}⟨310⟩ and "random" orientations. As the rolling texture in the recovered material was extremely strong (96 – 98% of all orientations), nuclei of the rolling texture components were susceptible to the effect of orientation pinning [9]. It is considered that in the subsurface layers orientation pinning experienced by nuclei of the dominant Cu component was especially pronounced, whereas the growth of nuclei with P, $\mathrm{Cube_{ND}}$ and other orientations was mostly unhindered [3]. As a result, during recrystallization (annealing at 300 °C for 2 h) the fraction of the rolling texture components in the subsurface dropped to 23%, while the fraction of P + $\mathrm{Cube_{ND}}$ components increased to 55%. In contrast, in the center, where orientation pinning was not as strong as in the subsurface, the fractions of the rolling texture and P + $\mathrm{Cube_{ND}}$ components after 2 h at 300 °C were 53% and 27%, respectively. These observations emphasize the importance of considering changes during recovery when examining recrystallization in heavily deformed metals.

Conclusions

The microstructural evolution during recovery in heavily rolled aluminum is strongly influenced by the initial spatial arrangement of different rolling texture components in the deformed material. In this material, coarsening of lamellar structures via TJ motion leads to the loss of HABs. This reduction in the HAB fraction is more pronounced in the subsurface layers than in the center, and is related to the initial differences in the distribution of the rolling texture components between the layers. Recrystallization in the center, which after initial coarsening still contains a large frequency of mobile HABs, proceeds more rapidly and with a higher nucleation density, resulting in a smaller recrystallized grain size than in the subsurface layers.

Acknowledgements

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